3-D Printing Principles, Processes and Applications

An Online Continuing Education Course for Engineers

Course Number: I-5002

Credit: 5 Hours / 5 PDH / 5 CPD

3-D Printing Principles, Processes, and Applications

R. Prakash Kolli, P.E., PhD

In this course, you will learn:

a. The history and background of 3-D printing
b. Important 3-D printing processes for polymers and applications
c. Important 3-D printing processes for metals and applications
d. The principles of 3-D printing, including 3-D models, slicing, design considerations and challenges, and materials

1. Introduction

Three-dimensional (3-D) printing or additive manufacturing is the process of taking 3-D drawings from computer-aided design (CAD) files and making 3-D solid objects from polymers, ceramics, composites, and metals. The creation of the solid object is an additive process that prints the object layer-by-layer. This process is inherently opposite to the subtractive processes of CNC-machining, cutting, drilling, and grinding. It is also different than formative manufacturing technologies such as casting or injection molding. Today, 3-D printing and subtractive processes are used in tandem. 3-D printing integrates 3-D design and modeling, materials, and manufacturing. Hence, a major benefit of 3-D printing is that it can produce geometrically complex shapes at a much lower cost than conventional methods. On the other hand, 3-D printed components require post-processing for optimal mechanical properties and surface finishes and may have lower accuracy and tolerances than parts fabricated by conventional methods. It is for this reason that subtractive processes are often used in conjunction with 3-D printing.

In general, 3-D printing processes can be broadly divided into ones that process polymers and ones that process metals. Ceramic and composite printing processes often fall in between these two using both polymer and metal 3-D printing processes depending on the material. The three major polymer 3-D printing processes are Fused Deposition Modeling (FDM), Stereolithography (SLA), and Selective Laser Sintering (SLS). The major metal 3-D printing processes are Direct Metal Laser Sintering (DMLS), Directed Energy Deposition (DED), and Binder Jetting. Other processes and categories exist for both polymers and metals, and new technologies are being researched, but the ones listed above cover the most commonly used ones. Since its inception, 3-D printing has progressed rapidly from use for visual prototypes to rapid prototypes to functional prototypes to fully functional parts in many industries.

In this course, we will first cover the interesting early history of 3-D printing starting in 1981. We then consider polymer 3-D printing processes, including Fused Deposition Modeling (FDM), Stereolithography (SLA), and Selective Laser Sintering (SLS). This is followed by a discussion of metal 3-D printing processes, including two powder bed fusion methods of Direct Metal Laser Sintering (DMLS) and the functionally very similar Selective Laser Melting (SLM), powder Directed Energy Deposition (DED), and Binder Jetting. In the appropriate sections, we discuss other 3-D printing techniques that are similar to the aforesaid ones. We discuss the principles, advantages and disadvantages, materials, and applications of each process. We consider post-processing at various points in the text. Next, we examine the principles of 3-D printing, including 3-D solid models, slicing of the CAD model, and design considerations and challenges. In the final section, we discuss different materials that are commonly printed. We discuss the benefits and limitations of 3-D printing and each process in the text.

2. Early History of 3-D Printing

2.1. History of Stereolithography (SLA)

The modern concept of 3-D printing is fairly new. Although not well known, one can trace the history of the modern concept of 3-D printing back to the Japanese inventor Dr. Hideo Kodoma of the Nagoya Municipal Industrial Research Institute (NMIRI) in 1981. He described the process of building a solid object layer-by-layer using ultraviolet or 'UV' light. In his method, a 3-D object was fabricated by building a part in layers where a mask was used to control exposure to the UV light, Figure 1. Specifically, he filed a patent application for a rapid prototyping device where a photosensitive polymer resin or 'photopolymer' was polymerized by UV light creating solid objects. Notably, Dr. Kodama was the first person to file for a patent of this sort. He filed a patent in Japan for this idea and technology but missed the one-year deadline for filing, so the application was denied. However, Dr. Kodoma's idea is often considered the ancestor of the Stereolithography apparatus or 'SLA.'

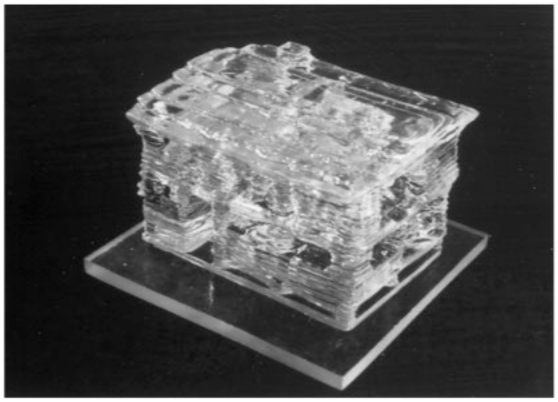

Figure 1. An early part fabricated using Dr. Hideo Kodoma's rapid prototyping technique.

The idea of developing a rapid prototyping device continued to evolve. In the early 1980s, a French team comprised of Jean-Claude Andre of the French National Center for Scientific Research (CNRS), Olivier de Witte, and Alain le Mehaute of Alcatel tried to develop a method to produce complex solid parts using liquid monomers that can be cured by UV lasers. The trio filed for a patent in 1984 but was forced to abandon the project due to lack of funding and business interest.

This brings us to Dr. Charles Hull, who today is credited as the inventor of Stereolithography. At the time, he was working for a tabletop and furniture maker. He suggested using the company's UV lamps to cure a photosensitive resin layer-by-layer. Only three weeks after the French team filed for their patent, Dr. Hull filed his patent application titled "Apparatus for production of three-dimensional objects by stereolithography" in 1984, which was granted in 1986. The patent described the application of lithographic techniques to produce three-dimensional objects employing computer-aided design (CAD) and computer-aided manufacturing (CAM) techniques. The patent also describes the term 'Stereolithography' and using the apparatus for models and prototypes in the design phase or even as a manufacturing system. Dr. Hull used this patent as the basis to start the company 3D Systems, which eventually released their first commercial product, SLA-1, as seen in Figure 2 below, in 1988. The SLA-1 was essentially the first commercial product to print real physical parts from digital or computer-generated files.

Figure 2. The first commercial Stereolithography 3-D printer, which was called the SLA-1. The technology was invented by Dr. Charles Hall. In 1987, the American Society of Mechanical Engineers (ASME) designated the SLA-1 as a Historic Mechanical Engineering Landmark.

From this point, the chronology of the early history of 3-D printing progresses rapidly. Two other important 3-D printing technologies were invented in these early years approximately in parallel with the SLA technique. The first was Selective Laser Sintering or 'SLS,' and the second was Fused Deposition Modeling or 'FDM.'

2.2. History of Selective Laser Sintering (SLS)

In 1986, the SLS technique patent was filed by Dr. Carl Deckard, a student at the University of Texas-Austin working on his master's thesis under the guidance of Professor Joseph Beaman. The SLS technique used polymer powder instead of a polymer resin. Dr. Deckard's early academic machine named 'Betsy" could only produce simple cubes of plastic, Figure 3. But it proved the SLS concept. The patent was titled "Method and apparatus for producing parts by selective sintering" and was filed in 1986 and granted in 1989. The patent discusses using a directed energy beam to selectively sinter a powder to produce a part. It also discusses a computer-aided laser apparatus and a CAD/CAM control mechanism to control the geometry.

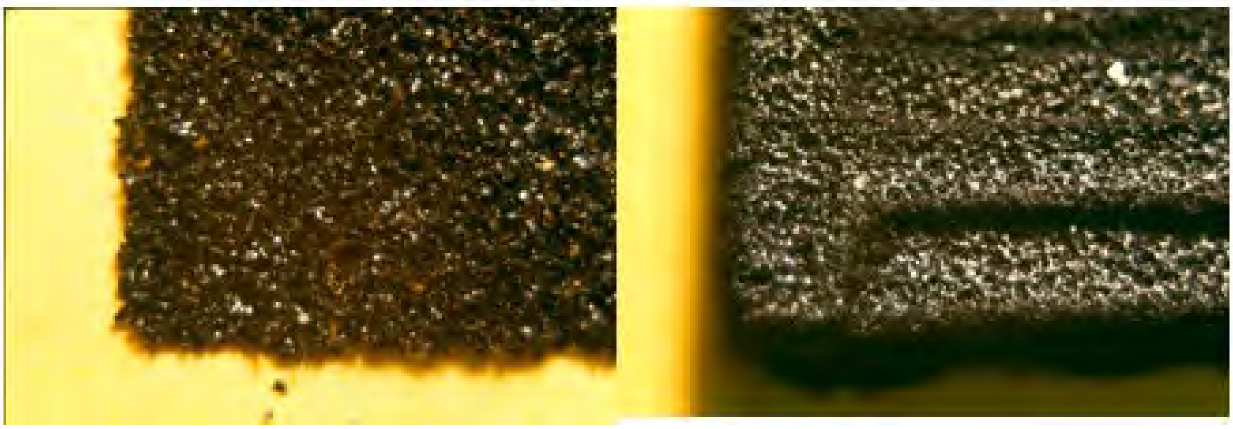

Figure 3. Images of the first plastic powder used by Dr. Deckard in SLS before sintering (left) and after sintering (right).

The University of Texas-Austin licensed the SLS technology, and this was the basis of the company Nova Automation that was formed in 1987. This company became Desk Top Manufacturing (DTM) in 1989. After the company secured funding from Goodrich, the first commercial SLS machine models were built in 1989. These machines were called the Mod A, Mod B, and the 125s. Only four of the 125s were produced, but none were sold commercially.

Approximately in parallel, Dr. Deckard completed his Ph.D. under Professor Beaman, working on developing the concept further using the "Betsy" machine. The two filed a second patent application titled "Selective laser sintering with assisted powder handling" in 1989, which was granted in 1990. Dr. Deckard, now a post-doc, along with Paul Forderhase, designed and built a second academic machine called "Bambi." This machine was integrated with CAD software.

DTM built the first modern production SLS machine called the SinterStation 2000. Several other models of the SinterStation were built after the first one. Eventually, Goodrich sold its majority share to a group of private investors. The company was later acquired by 3D Systems in 2001.

2.3. History of Fused Deposition Modeling (FDM)

The third 3-D printing technology developed around the same time was Fused Deposition Modeling or 'FDM.' The FDM technology was developed by Scott Crump in 1988. This technique involves melting a polymer filament and depositing it on a base plate in a layer-by-layer process to create a 3-D object. The story goes that Scott Crump came up with the idea for this new technology when he attempted to create a toy frog for his daughter using a hot glue gun loaded with a mixture of polyethylene and candle wax. After struggling to do it manually, he envisioned a way to automate the process and build the shape by creating a series of thin layers stacked on top of each other. His idea was, basically, to reverse the milling process. But rather than removing material from a block in a step-by-step process, he envisioned building up an object from scratch in a layer-by-layer process.

Scott Crump filed a patent application titled "Apparatus and method for creating three-dimensional objects" in 1989 that was granted in 1992. The patent discusses using a moving dispensing head to deposit material that solidifies at a predetermined temperature to create 3-D objects. The patent also states that the apparatus is driven by computer-generated code using CAD software. Lastly, the patent discusses producing 3-D objects by depositing repeated layers.

The FDM technology was the basis for the founding of Stratasys in 1989 by Scott and Lisa Crump. The first commercial FDM 3-D printer called the Stratasys 3D Modeler, was developed in 1992, Figure 4. The second commercial product, the Benchtop, was produced in 1993. FDM has developed into the most common of all 3-D printing technologies due to its simplicity and comparatively low cost. It is essentially an advanced glue gun. In addition, the core patent expired in 2009, and this resulted in many do-it-yourself (DIY) and low-cost FDM printers being released onto the market.

Figure 4. A picture of the 3D Modeler, the first commercial FDM 3-D printer developed by Stratasys.

2.4. Development of Other 3-D Printing Processes

Today, these three technologies serve as the major foundations of 3-D printing. The FDM technique is based on material extrusion through a heated extruder head. This differs significantly from the SLA technique and the SLS techniques that rely on UV light or an energy beam, respectively. There are alternative technologies that have developed from these three technologies or are very similar to these three technologies.

For instance, Direct Metal Laser Sintering (DMLS) was developed by the German company EOS in 1989. The method is conceptually similar to SLS, but instead, it is optimized to print metal objects using high-power lasers and metal powder. Note that Dr. Deckard's 1989 patent mentioned not only plastic powder but also metal, ceramic, and polymer materials. Electron-Beam Melting (EBM) for metal powder was developed by ARCAM in the mid-to-late 1990s. This process is conceptually and functionally similar to DMLS or SLM but uses an electron-beam or e-beam as the energy source to print metal objects from metal powder. Binder Jetting, which is based on inkjet printing technology similar to a 2-D printer, was developed at MIT in 1993. The first commercial Binder Jetting 3-D printers for metals were brought to the market by ExOne in 1998.

There are also a few other methods that have been developed more recently based on alternate foundational techniques. For example, electron-beam melting by wire or Electron-Beam Additive Manufacturing (EBAM) was developed by Sciaky in the 2010s. This technology was derived from metal wire welding processes, but instead of joining two objects together, EBAM creates a metal object using metal wire in a layer-by-layer deposition process. Extrusion processes that are conceptually similar to FDM were developed for composite rods or filament consisting of metal powder in a thermoplastic polymer matrix in the 2010s by Markforged and Desktop Metal. This allowed metal objects to be printed using extrusion-type 3-D printers followed by sintering. Subsequently, this technology was extended to 3-D printing of continuous carbon, glass, and Kevlar fiber-reinforced composites.

3. 3-D Printing Processes Today

In general, 3-D printi... CAD model of the object to be printed. This m... ng software into layers and translated into G-cod... printed individually in a layer-by-layer proces... printer depends on the material, resolution, w... al properties, cost, surface finish, and oth... n, we focus on the different polymer and ... ics. We cover other aspects of 3-D printing

3.1. *Fused Depositi*

3.1.1. *Principles of FD*

Fused Deposition ... nent Fabrication (FFF). It is a material ext... plastic continuous filament. The filament is ... ated and can move in 3-axes, as seen in Figu... pushed through the nozzle as a thin strand. Th... or *x-y* plane in a path predetermined by the soft... of material. The layer solidifies upon cooling.